Renewable and Sustainable Energy Reviews 32 (2014) 869–889

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Global experience with jatropha cultivation for bioenergy: An assessment of socio-economic and environmental aspects

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ARTICLE INFO

Article history:
Received 3 April 2013
Received in revised form
21 November 2013
Accepted 4 January 2014
Available online 13 February 2014

Keywords:
Jatropha
Sustainability
Smallholders
Plantation
Food security
Economic feasibility

ABSTRACT

This is an assessment of key economic, environmental and social issues pertaining to jatropha biofuels, based on almost 150 studies covering 26 countries. The assessment aims to furnish a state-of-the-art overview and identify knowledge gaps. So far, total jatropha production has remained small. Numbers and value of jatropha projects have even declined since 2008.

The economic analyses indicate minimal financial feasibility for projects. Yield increase and value addition (e.g., through utilising by-products) are necessary. Plantations seem to fare the worst, mainly due to the higher financial inputs used in a plantation setting and the still limited yield levels. Smallholders can only achieve financial feasibility in low-input settings and when opportunity costs are low. Unfortunately, hardly any Cost Benefit Analyses (CBA) are based on real data; partly due to a lack of long-running jatropha projects.

The environmental impact varies greatly across locations. Most studies indicate significant Greenhouse Gas (GHG) benefits over fossil fuels; however, this is only achieved with limited inputs and no loss of high C-stock biodiversity. The determinants in Life Cycle Analyses (LCA) are yield, input level, by-products utilisation, transesterification, transport distances, and land cover. More LCA research is required with more accurate data, and focusing on nitrous oxide emissions and the relation between production intensity and biodiversity impacts.

Minimal negative social impacts have been revealed so far, but discontinuation of projects affects communities through income losses and fostering more negative attitudes towards new projects. Moreover, hardly any studies quantify social impact comprehensively. Detailed data collection is necessary, involving baseline studies to start with.

If its financial feasibility is improved, jatropha can still become an option for sustainable energy production, GHG mitigation and rural development, especially through smallholder models. Successful implementation requires careful advance assessment of local circumstances, such as the political climate, gender aspects and land ownership structures.

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2014.01.028

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1. Introduction

Jatropha (*Jatropha curcas* L.) is being promoted as a potential renewable energy source as the tropical woody perennial tree or shrub species may survive in harsh climate and soil conditions. The current potential for producing jatropha biodiesel in arid and semi-arid areas in eight countries in Sub-Saharan Africa can be as large as 600 PJ yr^{-1} [1]. Furthermore, it is listed by the IPCC[1] as one of the potential bioenergy crops, with estimated costs of around 3.2 US \$ GJ^{-1} [2]. However, there is insufficient knowledge about some of the agronomic, socio-economic and technical aspects of the jatropha value chain and its implications for the sustainable livelihoods of local communities. Despite these uncertainties, large numbers of projects on different scales and with varying objectives have been implemented to develop viable bioenergy cropping systems. A study by GEXSI identified 242 projects in 55 countries [3]. In 2008, this study projected that the total global area under jatropha cultivation would grow to 5 million ha in 2010. This was at a time when jatropha was receiving a great deal of attention and this projection raised high expectations. Later studies lowered the expectations, for example Achten et al. [4] and GTZ [5], or were even quite negative, such as Kant and Wu [6]. At the same time socio-economic and environmental sustainability issues for biofuels were becoming more important, as evidenced by, for example, the formulation of criteria by both the Roundtable on Sustainable Biofuels (RSB) and the Global Bioenergy Partnership (GBEP) [7].

The focus on the viability and sustainability of jatropha as an energy crop has led to an increasing number of research publications, project results and experiences of different aspects of the jatropha value chain in various reports. These publications focus on different aspects, for example on cultivation [8–10], processing and technical properties [11–15], market prospects [16], and the impact on the environment [17,18]. In addition, different business models and impacts on farming systems have been assessed [19,20], as well as the impact of the policy environment [21]. Some publications describe a certain aspect of the value chain, whereas others focus on a specific country (such as Mshandete [22], and Liu et al. [23], focusing on Tanzania and China, respectively) or on one business model (for example Brittaine and Lutaladio [24], who focused on smallholders). Furthermore, Carels [25] published a review including agronomical and technological aspects, while Abdulla et al. [26] compiled a review on technical issues only. In addition to being heterogeneous, a large share of the literature is based on secondary sources that are not necessarily accurate and lag behind the fast-changing realities on the ground. The jatropha sector is dynamic: many new projects are starting up while others are being discontinued. Both successes and failures could provide valuable lessons if analysed systematically.

The objective of this paper is to provide a comprehensive overview of recent literature based on information from ongoing and discontinued jatropha projects, which analyses the lessons learned so far and identifies knowledge gaps by evaluating and screening against generally agreed socioeconomic and environmental sustainability criteria. Although agronomy and technology are important aspects in jatropha cultivation and processing, these aspects are not part of a sustainability framework such as RSB or GBEP. However, they are essential for increasing the efficiency of the cropping system and thus the various impacts. Several studies have taken the technical aspects into account, such as Silitonga et al. [27] and Shahid and Jamal [28]. The main conclusion from these studies was that it is technically possible to use jatropha biofuel in diesel engines. However, more research is required to gain better insight into the lifetime of the engine. The agronomic aspects are currently being studied in long-term projects such as [29,30]. Knowledge gaps on agronomy issues are reviewed in [31].

This paper starts with an overview of the global jatropha sector (Section 2); subsequently, the aspects included in the review are discussed (Section 3). Section 4 presents an overview of the studies used and Section 5 provides details on the analysis of these studies. Knowledge gaps are identified in Section 6 and lastly conclusions (Section 7) and recommendations (Section 8) are provided. Throughout this assessment, the term *jatropha oil* is used for both jatropha biodiesel and jatropha Straight Vegetable Oil (SVO); some studies refer to jatropha biodiesel as Jatropha Methyl Ester (JME).

2. Status of jatropha projects/overview of the sector

In 2008, 242 jatropha projects were identified as carried out or about to be carried out, around the world. These were both small-

[1] Intergovernmental Panel on Climate Change.

scale projects for local energy production and large-scale projects aimed either at establishing a national supply base or at production for export. Not all projects have received the same amount of publicity in the literature. There are also numerous jatropha projects that either have not yet started their operations, despite persistent publicity, or have had to scale down or even close down operations without adequate reporting. Therefore, in addition to literature sources, numerous field visits, contacts with project managers, and interviews with employees took place over the period 2006–2012 to compile this paper. Based on these sources, Fig. 1 presents the countries with ongoing jatropha projects.

A large number of jatropha projects have been implemented in Asia (India and Indonesia), Africa (East and West) and Latin America (Mexico, Brazil). Although many of them have ceased (part of) their operations. This is confirmed by [16,32], who mentioned that the main countries with current jatropha activities are India, Indonesia, Mozambique, Tanzania, Madagascar, Mexico and Brazil. The majority of the amount of ha planted is found in Asia (85%) and Africa (13%) while only 2% is reported to have been planted in Latin America, according to the study by GESXI [3]. Different business models and scales are being applied, from smallholder models with a centralised processing unit, participatory village systems aiming for rural electrification and soil conservation to large-scale centralised plantations. Some large-scale plantations received bad publicity and some had to shut down due to cashflow problems, e.g. in Tanzania, Mozambique and the Philippines (BioShape, Energem, Sun Biofuels) [33–36]. Unjustified high yield expectations are often at the basis of these cashflow problems. Furthermore, 4 out of 5 jatropha investments listed and analysed by Hardman & Co have seen a decline in value, the largest drop noted by D1 oils which went from 32 m£ at listing to 4.6 m£ in February 2011 [37]. In addition to high yield expectations, the decline in value is caused by losses on investments in biofuel refinery capacity and by an unfavourable location of the jatropha plantations. On the other hand, the aviation industry has shown an interest in utilising jatropha oil as jet fuel. Several test flights have been performed, for example in 2008 by Air New Zealand in cooperation with Boeing and Continental airlines, and later with China Airlines [37,38]. Still, so far the volume of jatropha oil in the total of consumed aviation fuels has remained relatively small (50,000 l jatropha oil was consumed by the Air New Zealand flight), not exceeding a few hundred thousand litres. Currently some pilot projects are being executed that attempt to certify jatropha production under a sustainability certification scheme (Fair Trade, NTA8080 and RSB). This could help to separate sustainable practices from unsustainable ones.

There are also several on-going research projects [32]. For example, there is a project at Leuphana University in Germany, where researchers are compiling an overview to assess the current and future production potential of sustainable fuels, including jatropha [39]. As mentioned above, there are long-term studies on agronomic issues [29,30], and there are research projects on socio-economic and sustainability issues by several NGOs (e.g. HIVOS, ActionAid) and research institutes such as Utrecht University, Eindhoven University of Technology, Plant Research International and Leuven University. In addition, Groningen University and the University of Hohenheim are two of the institutes that are currently assessing technical issues. Many of the jatropha projects that have been initiated in the last five years have been discontinued or have slowed down their pace of implementation. This makes it hard to collect data and consider the long-term impact. The data used in this assessment are based as much as possible on projects that were actually executed; however, some of these projects have been discontinued since then. Nevertheless, we can still learn some valuable lessons from these projects.

3. Review methodology and issues covered

The analysis of the studies was based on the common core sustainability principles and criteria formulated by various working groups (e.g. RSB and GBEP) and the Cramer criteria [7,40–44]. Also, sustainability issues that were considered to be especially relevant to Africa, as listed by e.g. Amigun et al. [45], were taken into account. These were: food versus fuel trade-offs, land use and tenure security, climate change and environment, impact on poverty alleviation and gender issues. Furthermore, for the analysis we made use of Gasparatos et al. [46], who analysed drivers, impacts and trade-offs of biofuels production and use. In addition, they examined the following aspects: the impact of biofuels production on ecosystem services and biodiversity (provisioning, regulating and cultural services and biodiversity) as well as on human wellbeing (rural development, energy security and access to energy resources, food security, health, land tenure and displacement, and gender issues). From these various sources, we created an amalgamated comprehensive list of commonly used sustainability aspects on three areas of concern; economic, environmental and social, that were also frequently covered by the studies [7,40,43–46]:

- Economic feasibility
- LCA and energy analysis
- Biodiversity
- Food security
- Local prosperity (or rural and social development)
- Labour/working conditions (or human/labour rights)
- Gender

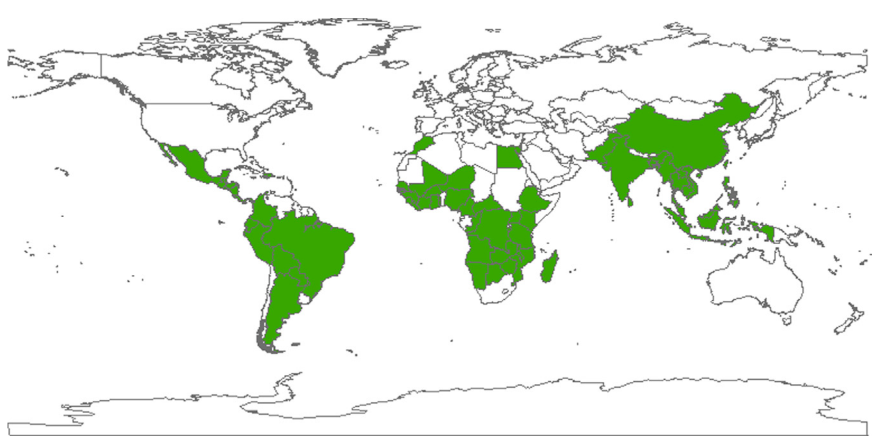

Fig. 1. Countries where jatropha activities have been reported. *Note*: Russia was not taken into account in the GEXI study.
Sources: based on [3,27,154] and fieldwork.

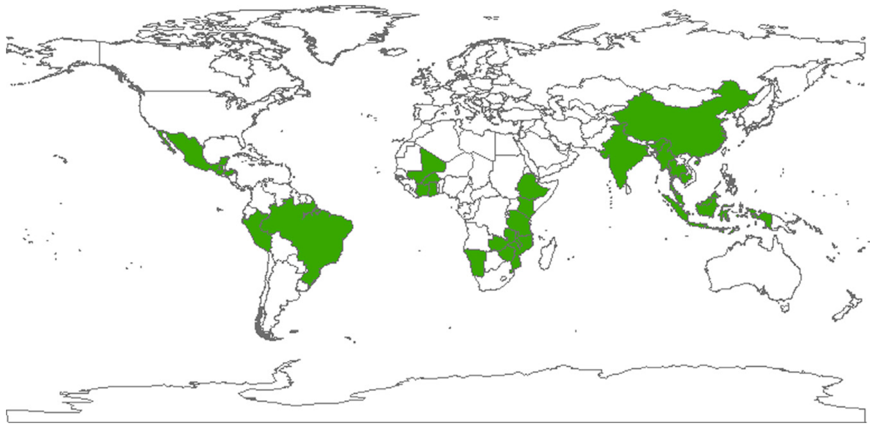

Fig. 2. Geographical coverage of jatropha literature taken into account in this study.

Whenever possible, two business models that were expected to yield very different results were distinguished throughout the analysis: the smallholder model (sometimes referred to as out-grower model) and the plantation model. Smallholders are small-scale farmers who produce either independently or for a processor in a contract farming model, whereas a plantation is a large piece of land, worked by employees who are paid to harvest the seeds. There are other options or combinations possible, but at this moment these two models are observed most often.

For each of the eight aspects, the facts from the studies, methodological aspects, an explanation of the differences and an assessment of the quality of the study and the knowledge gaps are included. The studies are scored as positive, neutral or negative, depending on the main conclusion of the study. Some studies contain both a negative conclusion (for example large-scale plantations are not feasible) and a neutral one (for example smallholder jatropha cultivation is only marginally profitable or under certain conditions); such studies are listed both as negative and as neutral. Summary tables per aspect that list these scores and include the country of study, source of data and main conclusions of the studies are provided in Appendix A.

4. Studies used in this assessment

A total of 200 studies that cover the aspects were identified, of which 147 were selected for further investigation.[2] One of the key selection criteria was that studies should relate to projects that are being or were actually executed; furthermore, studies based on primary data were taken into account as much as possible.

4.1. Geographical coverage of the studies

A large number of studies on jatropha are available. Many are peer-reviewed articles published in scientific journals, but there is also more 'grey' literature, including field reports and reports from NGOs. In this paper, a comprehensive and state-of-the-art overview has been compiled that focuses predominantly on literature from the period 2007–2012, in order to avoid the presentation of outdated information. Some earlier studies have been taken into account as well since they are frequently cited and widely used. Only literature in English has been considered; as a result, studies in French, Spanish or other languages have not been taken into account, with the exception of one study in Dutch [47] and one in Spanish [48]. The regions on which the literature was based were Sub-Saharan Africa (SSA), Latin America (LA) and Asia (A). Fig. 2 presents an overview of the 26 countries represented in this analysis.

A large number of studies focused on SSA (71) and Asia (37). Of the 113 studies that were country-specific, and the 71 that focused on SSA; most were based on data from Tanzania (31), Mozambique (14), Mali (5) and Kenya (5). In Asia the largest number of studies focused on India (16), while for Latin America (8 studies in total) this was Honduras (2). The small number for LA is partly due to language limitations and partly because LA only has 2% of the total amount of jatropha (ha) planted [3]. The remaining studies either focused on other countries or did not have a specific country focus.

4.2. Types of study

The studies included a large number of scientific journal articles (66), research institute reports such as FAO and ICRAF (27), NGO reports (21) and reports from industry including consultants (7). There were also 6 governmental reports, 17 Master thesis and 3 PhD thesis.

4.3. Quality and data source

Around 46 studies were based on field data or interviews with stakeholders in the country of study. However, for some studies it was difficult to identify the original sources of data. Around 47 studies were exclusively based on secondary sources (50 studies not indicated; see Table 1). In Table A-4 in Appendix, details on the number of interviews per study is provided (if available).

In total, 58 reports were found to include one or more social aspects, 37 included economic aspects and 50 reports included environmental aspects. Furthermore, there were 45 studies that specifically focused on smallholder systems and only 21 focused on large-scale plantations. There were more studies on social aspects than on economic or environmental aspects. Within the area of social issues, some aspects were included in only a few reports, such as energy balance, biodiversity and gender issues. In the studies based on primary data, only the aspects economic feasibility, local prosperity and food security were relatively well-covered.

5. Analysis of the studies

In Section 5.1 the results of the analysis on economic aspects are presented, Section 5.2 is based on the environmental impacts analysis while Section 5.3 analyses social issues. Each section describes the following four aspects: facts from the studies,

[2] See references of the main article as well as of Appendix. Full details of the studies are furthermore available upon request.

methodological aspects, an explanation of the differences and an assessment of the quality of the study.

5.1. Economic aspects

A total of 37 studies took economic aspects into account. Table A-1 in Appendix A summarises the results of the studies with respect to the current feasibility of jatropha projects (cultivation and/or processing).

In total, 10 studies were positive about the economic viability of jatropha, and 11 were negative. The majority (21) was partly neutral and indicated only marginal profitability or concluded that projects need to achieve certain yields to be viable. So in general the financial feasibility (Net Present Value: NPV) of jatropha projects is not deemed to be high. The studies indicated the following reasons for this low profitability: low yields, low price of fossil fuel, low price of by-products (although there is the potential of use as animal feed if it is feasible to detoxify the seedcake) and the high amount of labour required for harvesting. Overall, the uncertainties are considerable and therefore the results of jatropha projects vary widely. Of the studies, 25 wholly or partly focused on smallholders whereas 17 focused on plantations.

Subsidies may be provided to increase profitability for farmers in the cultivation stage. This happens in, for example, India and in Mexico [49–51]. In India, subsidies for smallholder farmers are provided at 90% subsidy on irrigation systems and 40–100% for land preparation. Funding is provided by various sources including the government [49]. In Mexico, the subsidy provided does not cover the real cost of establishment and maintenance. The number of farmers willing to participate is higher if subsidies are available. However, this affects the overall profitability of jatropha; besides, in Mexico it was observed that the subsidy was the farmers' primary motivation to grow jatropha [50].

5.1.1. Cost benefit analysis results

Only 9 studies used Cost Benefit Analysis (CBA) methodology or aspects of it; 7 of these were published after 2008. The best-quality CBA research was conducted in Kenya and Tanzania. Only 5 studies included Net Present Value (NPV) calculations, and the values found varied greatly. For example, Wiskerke et al. [52] calculated an NPV for different systems of $-10{,}000$ to 9500 $\$\ ha^{-1}$ in Tanzania, Wang et al. [53] calculated around -2000 $\$\ ha^{-1}$ in China, while Basili and Fontini [54] found 56,000–2 M$\$\ ha^{-1}$ (calculated with different discount values and cost options). The assumptions in these studies vary to such an extent that it is not possible to make a direct comparison of the results. Moreover, there was great variation in the calculated internal rate of return (IRR) values. For example, Loos [9] found 16–65%, GTZ [5] found 14–24% in Kenya and Feto et al. [55] found 12–16% in Ethiopia. Again, the scope of the studies varied greatly, from smallholder farming to the IRR for processing. The cost price of jatropha oil mentioned in the studies was for example 0.35–0.42 $\$\ l^{-1}$ (excl. processing costs) in Tomomatsu and Swallow [56], 19.6 $\$_{2007}\ GJ^{-1}$ or 0.75 $\$_{2007}\ l^{-1}$ in Wiskerke et al. [52] and 0.5–0.6 $\$_{2006}\ l^{-1}$ in Indonesia, calculated by Silitonga et al. [27]. In Honduras, jatropha oil was actually produced and costs were calculated as 0.77 €$\ l^{-1}$ for SVO and 1.13 €$\ l^{-1}$ for jatropha biodiesel, while in Mozambique jatropha SVO was 0.83 €$\ l^{-1}$ [57]. Important variables that determine the CBA were purchase or lease price of land, cost of inputs (mainly fertiliser), workers' wages (and thus specific for the country of production), and the amount of labour required for cultivation. Wang [53] and others indicated that the majority of costs occur in the feedstock production stage.

The available studies about the expected economic viability of jatropha-based activities concentrated heavily on Eastern and Southern Africa and India: 10 focus on Tanzania, 5 on Kenya, 3 on Mozambique and 6 on India.

5.1.2. Methodological aspects

There are 19 studies that were partly or fully based on self-collected primary data A total of 10 studies applied a CBA that included NPV or IRR calculations; 6 of these wholly or partly focused on plantations and 7 on smallholders.

Two major problems were found to have a major impact on the results: (i) estimates of seed yields have often been unrealistically optimistic in the light of the emerging body of evidence about jatropha's agronomic performance; and (ii) land and labour resources have often not been represented at their full opportunity costs. Together, these problems have given rise to over-estimations of expected profitability. They are discussed in the paragraphs below. Methodological issues were also noted, such as different time frames and different discount factors, which makes it hard to compare the results of the studies. The discount factor also influences the results of the CBA [54]. For example, Wang et al. [53] used a discount rate of 8% (and a 30-year time horizon). At a discount rate of 6.8% both jatropha SVO and biodiesel yield the same NPV; biodiesel has a higher NPV than SVO at discount rates above 6.8%. There is also a significant variation in the time horizon used; a representative period would be 20 years since jatropha only starts yielding after several years. Many studies mention potential yield improvements which would make the economic viability of jatropha more positive. Furthermore, the prices paid for seeds greatly influence the profitability for smallholders.

Table 1
Studies based on fieldwork or secondary data and number of peer-reviewed articles (not excluding each other).

Area of concern	Aspects	Studies based on primary data	Studies based on secondary data	Peer-reviewed articles	Total number of studies identified
Economic	Economic feasibility	15	17	14	37
Environmental	GHG/LCA	9	16	18	37
	Land use carbon stock	5	8	6	14
	Energy balance	1	0	2	2
	Biodiversity	2	1	3	9
Social	(Local) food security	13	6	11	28
	Local prosperity (rural and social development)	19	8	14	40
	Labour/working conditions (human/labour rights)	9	1	2	11
	Land ownership/land rights	8	3	5	21
	Gender	6	1	3	11

Table 2
Specific dry seed yield data from the studies.

Country	Setting	Yield Kg/ha/yr	Source
Tanzania	In semi-arid conditions	3200–4800	Kempf [148]
Kenya	Rainfed irrigated	3700[a] 7900[b]	Tomomatsu and Swallow [56]
India	From 5th year onwards	1800	Francis et al. [149]
Tanzania	Low inputs to high inputs	1000–3000	Struis [79]
Tanzania	In year 3 estimates, smallholders semi-arid	259 1500–5200	Loos [9]
Mozambique	Highest estimate	300/4000	Ecoenergy International Corporation [150]
Tanzania	From year 3 onwards in fertile area using occasional flood irrigation and virtually no fertiliser	1700	Messemaker [151]
Kenya	Shimba hills, Monsoon climate, rain twice per year, 400–1200 mm, sandy soil	250[c]	Moraa et al. [58]
Kenya	Semi-arid region, smallholders, yield estimate for mature trees (after 9 years)	420–1370[d] 150–500 270–450	GTZ [5] yield for monoculture, intercrop field and fence
Tanzania	Northern Tanzania, smallholders, rain twice a year, <1000–2000 mm, neogene soils, yield from year 5 onwards	2000[e]	Wahl et al.[126]
Tanzania	Based on literature from India	7000	Mulugetta [152]
India	Mature rainfed to mature irrigated	3450–5200	Estrin[124]
Tanzania	Northern Tanania, smallholders, semi-arid, from year 9 onwards	2 kg/shrub	Wiskerke [52]
India	(Tamil Nadu) rainfed or irrigated	450–750	Ariza-Montobbio and Lele [59]
India	For mature plantations	1000–1250	Various studies cited by Brittaine and Lutaladio [24]
India (south)	Tamil Nadu and Andhra Pradesh, smallholders, rainfall average 940–960 mm/yr, various inputs used, manure and irrigation	3–2500[h]	Axelsson and Franzén [49]
No specific focus	Worst-medium-best case estimates (from literature)	3000–5000–7000	Hawkins and Chen [37]
China	Yunnan province, plantation on marginal soil, fertilisers applied. Maximum yield from the 5th year onward	1485[f]	Wang et al. [53]
Indonesia	In poor soils 1 kg/tree, other soils 2–4 kg/tree	1590 kg/ha (oil)[g]	Silitonga et al. [27]
Mali Honduras	Smallholder farmers using low inputs, Mali average rainfall in the area 800 m and Honduras 1200 mm/yr small amounts of fertiliser or manure used, yield after 2 or 3 year	500 450[i]	De Jongh and Nielsen [57]

[a] Original data in kg/acre, 1500 kg, conversion factor 2.47.
[b] Original data in kg/acre, 3200 kg/acre, conversion factor 2.47.
[c] Original data 0.5 kg/tree and 100 kg/acre, conversion factor 2.47.
[d] Data obtained from 143 surveyed farms in Kenya of mostly 3 yr old, original data in kg/acre.
[e] 875 kg/ha was observed but only on one field, therefore the study used 2000 kg/ha as an estimate.
[f] Yields are based on field survey and literature.
[g] Value taken from various literature sources.
[h] Based on survey in 2005 and 2010 with in total 113 respondents, in total 21 respondents harvested jatropha.
[i] From good performing fields, although there are high yield variations between different fields.

5.1.2.1. Yield. Studies used yield estimates derived from different countries and different stages of maturity. For example, Moraa et al. [58] used yields of jatropha plants that had been planted in 2006 and had therefore not reached maturity, while Tomomatsu and Swallow [56] mainly used yield estimates from India, which seem very high. The study by GTZ [5] extrapolated actual yield patterns from 3-year plants to maturity, which is reached in year 8; this extrapolation was based on scientific literature, mainly from India. High and low yield scenarios were calculated in order to take uncertainties into account; in addition, a distinction was made between monoculture, intercropping and fence plantings. The estimated yields used by the various studies covering economic aspects range from around 3 to 7000 kg/ha/yr (see Table 2). However, if only observed yields are taken into account, the yield ranges from 0.4 to 2000 kg seeds/ha [31]. The sensitivity analysis performed by Wang et al. [53] revealed that even a yield of almost 4 t/ha/yr still leads to an unfeasible result for a plantation with a breakeven price of 0.70 €/l biodiesel while this price is 0.93 €/l at a yield of 1.5 t/ha/yr.[3] If CO_2 credits are included (at a price of 9.8 €/ton CER (Certified Emission Reduction), seed yield should be 2.3 t/ha/yr for financial breakeven [53]. In the study by Van Eijck et al. [20], doubling the yield almost triples the NPV: a yield rising from 1 t/ha/yr to 2 t/ha/yr leads to an increase in NPV from 15 to 41 M$/ha. Similarly, Loos [9] also indicated that yields should increase to above 2 t/ha/yr, while Ariza-Montobbio and Lele [59] indicated that yield should increase to above 2.5 t/ha/yr to make cultivation on a plantation viable. Thus, a yield increase to above 2–2.5 t/ha/yr seems the minimum yield for plantation systems. The maximum yield for jatropha is 7.8 t/ha/yr, so 2–2.5 t/ha/yr seems achievable [10].

In their assessment of the economic viability, studies generally emphasise the cultivation stage. Sometimes, but not always, this included a comparative viability assessment of different crops. A handful of studies also included the oil and biodiesel processing stages and the market situation with respect to jatropha by-products, and tried to assess their competitive situation versus competing products. However, most studies did not include a value for seedcake in the CBA.

[3] Exchange rate €/Yuan: 9.64 (February 2010, retrieved from www.oanda.com).

5.1.2.2. Cultivation costs. A number of studies differentiated between more than the two business models identified by this study; besides considering plantations and smallholders, they also looked at fence cultivation. The study by GTZ [5] was one of the very few studies that provided primary cost data. This study indicated that the establishment costs for fences are low and that fence cultivation is beneficial for farmers, as long as there is a market for the seeds.

The GTZ study calculated 824 $/ha establishment costs for mono plantations and 103 $/ha for fences. If it is assumed these are the only costs in the first 3 years of a jatropha project, these costs amount to approximately 325 $/ha (exchange rate November 2010) for a mono plantation scenario. Of this, 30% are labour costs, excluding opportunity costs of unpaid labour [5]. Some studies indicated that a subsidy is provided for farmers to cover their cultivation costs (e.g. [49]).

5.1.2.3. Prices paid for seeds. There are only limited differences between the prices paid to farmers for the seeds; they vary from 0.05–0.18 $ kg^{-1}, with short-term peak prices. In Mexico, 0.12–0.18 $ kg^{-1} is paid for seeds to keep jatropha SVO competitive with fossil diesel, although short term peak prices up to 0.54 $ have been reported [50]. In Honduras the price is around 0.10 $ kg^{-1}, while in Mali the price is 0.05 $ kg^{-1} [57]. In Tanzania seed prices are also around 0.10 $ kg^{-1} [60]. Roughly 4 kg of jatropha seeds is required for 1 l of oil. Therefore, the price of seeds is often established in such a way that jatropha SVO is competitive with fossil diesel.

5.1.3. Quality judgement and knowledge gaps

The evidence suggests that the financial feasibility of jatropha cultivation under current conditions and with the current state of knowledge and experience is quite poor. On fertile lands and with the use of irrigation and fertiliser, cultivation results in reasonable or even good dry seed yields of 2–4 t/ha/yr. However, under these conditions the same resources can produce far more profitable food crops. On wastelands with zero opportunity costs, yields would be far too low to be of economic interest (<1 t/ha/yr). For settings that include marginal and grazing lands, the opportunity costs of land and labour (and water supply) cannot be assumed to be zero, while yields will be modest unless substantial supplementary inputs, such as fertiliser and water, are provided. The unviability of this type of cultivation has been estimated quite convincingly for China by Wang et al. [53]. The findings for oil processing are not much better than for cultivation. At present, jatropha biodiesel cannot compete with fossil fuel on domestic markets. For jatropha to become a viable biofuel in those markets, its value chain needs to be more profitable. This may be achieved by finding higher-value uses for by-products (especially seedcake), further increasing oil-processing efficiency, developing seed varieties with higher and more reliable seed yields under semi-arid conditions, and optimising cultivation practices. However, considering the perennial characteristic of the crop, it is unlikely that these challenges will be resolved within a few years.

Currently, one of the most feasible scenarios that emerges from the studies is resource-extensive jatropha hedge cultivation. This practice has very low opportunity costs and can be undertaken on fertile lands with good water access. Therefore, some studies therefore state that jatropha cultivation other than as hedge plantings or small scale projects should not be recommended for the time being [5,61]. Furthermore, some projects focus on local self-sufficiency and link seed production closely to local processing and oil use. Such projects appear to have better potential for achieving financial viability than larger projects focused on the use of the oil in other places. This can be explained by the ability to return the seedcake to farmers as fertiliser and the use of jatropha SVO for local applications, instead of the production of more expensive biodiesel. Seed and oil production for export to the EU has been unprofitable due to stiff competition from subsidised bioethanol from the US. This may change when niche markets with high sustainability requirements develop, such as biokerosene feedstock for airlines, and when official biofuel sustainability norms come into force in the coming years.

Many studies lack original and measured field data, such as yields that are reliably measured and accurate cost data of the projects. These data are still scarce as most jatropha projects are in a too early stage to measure yields from mature plants, and no large quantities of jatropha oil have yet been produced in these projects. However, for large investments, more detailed information is necessary to design a proper business case and to prevent project failure.

5.2. Environmental aspects

The environmental aspects that have been included are Life Cycle Analysis (LCA) and energy balance, and biodiversity.

5.2.1. LCA and energy analysis

A total of 45 studies have taken environmental issues into account, of which 36 include LCA and 18 include carbon stock and energy balance calculations. As shown in Table A-2 in Appendix A, the scope and goal of different ecological assessments of jatropha bioenergy can differ widely.

Studies comparing jatropha biofuels to fossil fuels conclude that jatropha biodiesel is preferable over fossil diesel, based on the analysis of greenhouse gas (GHG) balances, excluding Land Use Change (LUC); however, this conclusion is sometimes based on estimated data and assumptions which are highly uncertain and/or whose validity is doubtful. These assumptions will be discussed in the next paragraph. Only if land with high carbon stock is converted to jatropha plantations, can the LCA be negative compared to fossil fuel. This is demonstrated in the sensitivity analysis of [62], for example. The IPCC has also included jatropha in their overview of renewable energy sources and the lifecycle GHG emissions of jatropha, about 25 to70 CO_2 eq/MJ fuel, falls within the range for palm oil of about 18 to 75 CO_2 eq/MJ fuel [63, Fig. 9.9].

Assessments comparing different biofuels sometimes reached conflicting conclusions, due to variations in local circumstances, differences in processes or differences in assumptions, especially with respect to by-product allocation. For example, some studies indicated that jatropha oil or biodiesel has a lower GHG emission than palm oil [64–66], whereas other authors, such as Lam et al. [67] and Veen and Carillio [48], concluded that palm oil leads to higher GHG savings than jatropha oil. In the IPCC study, which compared several biofuels, jatropha oil has emissions similar to those of palm oil, while rapeseed (EU) and soybean (US) have lower emissions, this is without considering LUC [63]. However, including LUC, jatropha is assessed as more having more favourable emissions than palm oil, with a range of -100 to 100 g CO_2-eq/MJ for jatropha and approximately -20 to 350 g CO_2-eq/MJ for palm oil. This result stems from the possibility of growing jatropha on marginal soils; palm cannot be grown on marginal soils.

An assessment of biogas production from jatropha concludes that it may be more efficient to use jatropha seeds for anaerobic digestion, rather than first obtaining oil and then producing biogas from the seedcake [68].

Centralised versus decentralised processing of the seeds can also make a difference: Reinhardt et al. [69] concluded that centralised jatropha processing facilities in India deliver better GHG results and need less fossil resources than decentralised ones. In centralised facilities, the longer transport distance is compensated by higher oil extraction and lower energy consumption during processing.

The studies use different functional units and are therefore difficult to compare. The 14 studies that include a percentage of emission reduction compared to fossil fuel are shown in Fig. 3. The black triangle indicates the average of the values mentioned in the studies, and the green bar shows the range (if applicable).

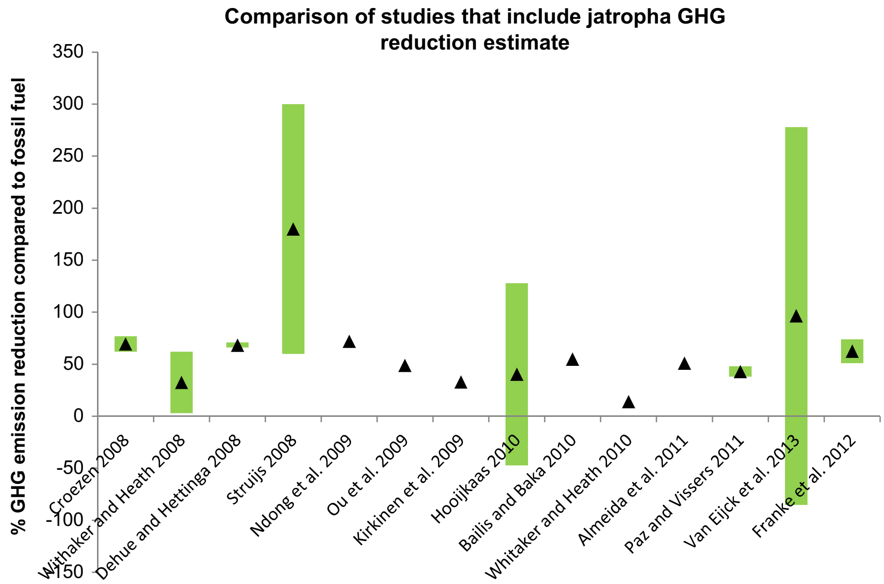

Fig. 3. Emission reduction % indicated by the studies, average (black triangle) and range (green bar) per study. *Note*: the range in Paz and Vissers [62] is 39–48%; however, in their sensitivity analysis their range is 15–74% emission reduction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

All averages indicate a reduction (from 14 to 180%) compared to fossil fuel, the total range of the studies is −85%–300%; the negative values are due to land use changes.

5.2.1.1. Methodological aspects. In addition to the factors mentioned above, there are important differences in the conclusions of the various studies which also derive from differences in their assumptions. These differences include yield, the way in which by-products are utilised, and the end-use (e.g. fuel or electricity). Furthermore, differences are due to methodological choices in different models, for instance in by-product allocation.[4]

As regards the cultivation stage of jatropha, it is striking that the differences in assumed seed yield are very high (Table 3). They range from 0.4 to 12 t/ha/yr.

The energy contained in the different by-products is high; therefore, the use of by-products has a great impact on the energy and GHG balances.

Regarding the energy use and GHG emissions of the different process steps, it has become clear that transesterification and fertiliser application are the main contributors. Gunaseelan [68] reports that 67% of the energy required is used in transesterification and 18% is used for fertilisers; in addition, transesterification is responsible for 52% of the GHG emissions and fertiliser use for 35%. However, emissions due to land use change have not been taken into account, even though they are an important factor. According to [70], the largest contributor to GHG emissions is the cultivation stage (45%), followed by the biodiesel utilisation stage (30%) and biodiesel production (28%); this study did not include any LUC effects. Ndong et al. [64] also concluded that the GHG emissions in cultivation constitute 52% of total emissions (mainly due to fertiliser), transesterification accounts for 17% of GHG emissions, whereas final combustion accounts for 16% (no LUC effects included). The study also calculated the energy consumption of all steps: transesterification 61%, transport (of all products) 15% and cultivation 12%. Thus, most authors agree that the cultivation stage is the largest contributor to GHG emissions, and transesterification accounts for the largest energy consumption in the process chain. In addition, one study added that irrigation is a major contributor to environmental impacts, as well as the end-use phase and land use changes [71].

Some authors include a **sensitivity analysis.** The following conclusions can be drawn from the review:

- According to Dehue and Hettinga [66], GHG performance is sensitive to oil and seed yield, but not as sensitive as expected, due to the relatively low GHG emissions in the cultivation, transport and extraction stages, compared to the emissions in oil transport and in the transesterification stage. Transesterification is the largest contributor (43%), followed by oil transport (34%) and land use change (15%). It is assumed that grassland is converted to jatropha plantations. Cultivation is 0% as it is assumed that no inputs are used.
- Whitaker and Heath [72] performed a sensitivity analysis on selected parameters and found that tree planting density, seed yield and seed oil content have a substantial influence on LCA results. In addition, the environmental impact of individual plantations is site-specific and depends on seed yield [73].
- Prueksakorn and Gheewala [74] concluded from their sensitivity analysis that the biodiesel yield, co-product yields, farm energy inputs, energy consumption in the oil extraction process and energy consumption in the biodiesel consumption process are the largest contributors to GHG emissions; however, they did not include LUC in their analysis.
- Arvidsson et al. [75] found that variations in crop yield and in nitrous oxide emissions from microbial activities in soil may cause significant changes in the results.
- The LCA is sensitive to seed yields (increase of 1 t/ha results in a 10% reduction of GHG). Besides, transport by truck instead of freight train has an impact similar to yield (564 km by train leads to a reduction by 8–14%). The energy consumption of the labour force has been included by using a worker's average daily ratio (2300 kcal/day); this reduces energy yield by 27%. Local use of jatropha biofuel instead of transporting the biofuel has important effects: the energy yield ratio rises from 4.7 to 26.4 and GHG savings increase from 72% to 85% [64].
- The sensitivity analysis performed by Paz and Vissers [62] showed that seed yield is by far the most important defining

[4] Dehue and Hettinga [66] conclude that RTFO has to change its co-product methodology allocation by energy content, in order to be consistent with the EC proposal [66].

Table 3
Seed yields used in the studies.

Location	Seed yield (t/ha/yr)	References
Malaysia min	0.4	Lam et al. [67]
Small holders Tanzania	1	Struijs [79, p. 38]
Critical for GHG reduction	1.25	Whitaker and Heath 73, p. xi]
Poor soils today	1.418	Reinhardt [69, p. 11]
Infertile soil	2.382	Stuttgart et al.in[67]
Poor soil optimised	2.382	Reinhardt [69, p. 11]
Average Indian village	2.5	Gmunder et al. [84, p. 350]
Seed yield India low	3	Dehue and Hettinga [66, p. 3+p. 27]
Raipur India	3.75	Whitaker [73, p. 6]
Ivory Coast	4	Ndong [64, p. 201]
India	4.05	Gunaseelan [68]
Poor soil best	4.436	Reinhardt [69, p. 11]
India	4.5	Achten et al. [71, p. 4]
India base case	4.5	Dehue and Hettinga [66, p. 3+p. 27]
India	5	Arvidsson et al. [75, p. 8]
Good conditions Malaysia	5	Lam et al. [67]
Malaysia	5	Lam et al. [67]
China	5	Ou et al. [65]
Peru average	6	Veen and Carrilo [48, p. 38]
India high	6.3	Dehue and Hettinga [66, p. 3+p. 27]
Perennial plantation Thailand	8.75	Prueksakorn et al. [74, p. 3]
Malaysia max	12	Lam et al. [67]
Mozambique, Manica	3	Paz and Vissers [62]
India Tamil Nadu	11	Pandey et al. [153]

parameter (using a yield of 1.5 instead of 3 t/ha/yr results in only 15% savings instead of 48%). Oil yield and the input of nitrogen fertiliser also have a significant impact. The influence of phosphate fertiliser is only minimal.

- The average sequestration rate by jatropha trees used by Ndong et al. [64] citing [69] is 900 kg C ha^{-1} yr^{-1}.
- Arvidsson et al. [75p8] concluded that a drop in seed yield from 5 t/ha to 0.5 t/ha would increase Global Warming Potential (GWP) by 770% whereas an increase in seed yield from 5 to 12 t/ha would decrease GWP by 43%.
- The main factors that Bailis and Baka [76] indicated in their sensitivity analysis are land use change and yield.

5.2.1.2. Quality judgement and knowledge gaps. The analysis revealed six critical aspects for the assessment of environmental impact of jatropha biofuels.

5.2.1.2.1. Land use change. This assessment confirms the patterns signalled in an earlier jatropha review by Achten et al. [71], i.e. cultivation on degraded soils and waste lands gives the greatest reduction in GHG emission. However, the GHG balance can turn unfavourable when cultivation leads to a reduction in the carbon stock by the removal of existing vegetation, for example when forest and woodland areas are used [20,48,66,69,76,77]. Arvidsson et al. [75] also concluded that the significant contribution of global warming potential originates from soil during cultivation.

5.2.1.2.2. Usage and allocation of by-products. The by-products of the production of biodiesel from jatropha (seedcake, biogas, glycerine) contain a large amount of energy; together, these products hold slightly more than half of the energy contained in biodiesel [67]. Prueksakorn et al. [78] reported that the energy content in the seedcake produced is almost double the energy contained in the biodiesel produced. Therefore, the use of by-products is crucial for the outcome of the LCA. The use for energy production allows a significantly higher GHG reduction than the use for fodder or fertiliser, due to higher fossil energy savings. This was shown in the study by Reinhardt et al. [69], who calculated LCAs of different value chains. If none of the by-products is used for energy, the energy balance is slightly positive: 0.89 MJ energy input per MJ Jatropha biodiesel output; however, if all by-products are used efficiently, the energy input per MJ Jatropha biodiesel output can be reduced to 0.16 MJ per MJ JME output [71].

5.2.1.2.3. Fertiliser usage. Applying N-fertiliser results in direct emissions and indirect soil emissions and leads to a significant worsening of GHG performance [79]. P-fertiliser and lime addition have only a limited effect on GHG performance [66]. Ndong et al. [64] also concluded that it is necessary to limit fertiliser use in order to reduce energy use and GHG emissions. Ou et al. [65] found that fertiliser input is a major GHG factor. Nitrogen emissions also have negative results in other environmental impact categories, such as eutrophication. Of course, there is a trade-off in applying less N-fertiliser on degraded soils and yield. Thus, fertilisation is necessary to maintain long-term seed yields; since the plant is not a nitrogen-fixing species, harvesting the seeds leads to regular nutrient removal [80,81]. According to Struijs [79], nutrients are the limiting factor in degraded soils in Northern Tanzania where the jatropha is cultivated; in such situations, eutrophication may be welcome. Moreover, as mentioned by Basili and Fontini [54], considering that fertilisation is responsible for 30% of the GHG emissions, the GHG balance can be improved by using natural fertiliser such as seedcake or organic manure, rather than mineral fertiliser, even though Reinhardt et al. [69] concluded that the energetic value of seedcake is more valuable. Furthermore, if seedcake is used as fertiliser, the GHG reduction performance of the jatropha chain will be significantly reduced because the seedcake is no longer an energy by-product to which part of the emissions can be allocated.

5.2.1.2.4. Nitrogen contributions to GHG. These are often only partly incorporated; however, Arvidsson et al. [75] concluded that more than half of global warming potential is caused by nitrous oxide emissions from soil. These emissions originate from both fertiliser and microbiological activity in the soil. The impact of nitrous oxide emissions may be underestimated.

5.2.1.2.5. Energy use in the transesterification phase. As transesterification is responsible for 23% of GHG emissions, the GHG balance can be improved by consuming the Straight Vegetable Oil (SVO) [54]. Ndong et al. [64] suggested that to reduce both energy requirements and GHG emissions, a reduction is necessary in the energy and chemicals used in the transesterification process. Alternatively, using jatropha oil in the form of SVO would reduce GHG emissions by 45% and energy use by 82% [64].

5.2.1.2.6. Transport. Long-distance intercontinental transport of seeds or oil has a major impact on the LCA. Ndong et al. [64] reported that oil transport from Ivory Coast to France claims 75% of the energy use of transport (around 12% of the total energy use in the jatropha diesel production life cycle). Local production of biodiesel would reduce energy use by 10% and reduce GHG emissions by 2% [64]. In some countries, due to bad infrastructure and inefficient combustion in heavy duty trucks, rail transport may be preferable for inland transport. In India, transport by train (0.19 MJ/tkm) instead of by truck (1.94 MJ/tkm) would improve overall GHG performance by 3% pt (111 to 118 kg CO_2 eq/t biodiesel; in [66]). Furthermore, a mobile expeller, if not changing oil yield and energy use, reduces GHG intensity by 75% for the extraction phase by reducing transport needs [66]. Reinhardt et al. [69] also indicated that transport has a large influence; the exact influence is determined by transport distances and modes, which in turn are influenced by the business model (e.g. central or decentralised processing), the factory capacity, land use intensity and yield levels.

Based on the literature reviewed in this section, it can be concluded that jatropha biofuels may contribute to significant GHG reductions compared to fossil diesel, especially when limited inputs are used and land converted to jatropha does not have a

high carbon stock (e.g. virgin Miombo Woodland or pristine forest). The main critical issues (which may also make the LCA negative) are: land use change and the initial carbon debt, the input used in the cultivation stage (especially fertilisers and pesticides), the use of by-products, energy use in the transesterification stage, and transportation mode and distance.

The issues discussed above demonstrate that an LCA should be performed for specific sites, for the specific jatropha products that will be used, and for specific business models. Except for location-specific data such as data on soil carbon and previous land cover, most data necessary to perform an LCA for jatropha is available; one of the most comprehensive LCA tools which includes relevant data is the GHG calculator developed by IFEU [82].

It is necessary to gain more insight into the specific environmental impacts acidification, eutrophication and nitrous oxide, as well as into how these impacts can be minimised. Moreover, the most efficient use of by-products is not straightforward, since they can be used as energy sources or as fertilisers. Some studies, such as Gunaseelan [83], included the production of biogas from various jatropha products (wood, seedcake), whereas others, such as Gmünder et al. [84], took the production of electricity into account. In still other studies, seedcake is used as a fertiliser and therefore no GHG emissions are allocated to the seedcake [82]. There will be trade-offs between the different dimensions of using the by-products of jatropha, including GHG emissions, cost-benefit, energy-efficiency, long-term soil health and yields.

5.2.2. Biodiversity

Nine studies investigated the impact of jatropha projects on biodiversity. Three of these studies focused on Tanzania, whereas the other studies all focused on different countries, see Table A-3 in Appendix A. Only two studies found a positive impact (increase of biodiversity), six were neutral and four found a loss of biodiversity. Only two studies actually measured or observed changes in biodiversity; families interviewed in Brazil by study [17], found that per family 0.72 h was deforested, and in Mexico [50] some deforestation was observed but only limited.

The impact on biodiversity varies with the specific location of the jatropha trees. Prueksakorn and Gheewala [74] found that there are two determining factors: previous land use and intensity of production.

5.2.2.1. Previous land use. In the projects in Mozambique visited by Schut et al. [85], the natural vegetation was cleared, but some indigenous trees were left. A study by Van Eijck et al. [20] measured the above-ground biomass in the area targeted for a plantation and found forests with high C-stocks. Some reports mention that existing projects have a potentially negative influence on biodiversity due to their location. In Mozambique, the ADPP/FACT project (in Bilibiza) is located in a National Park, and two other projects are located close to high-biodiversity areas [85], citing [86]. However, this negative influence on biodiversity may be avoided by not targeting forest areas or other biodiversity hot-spots for jatropha plantations. Fragmentation of forests has not been included in the studies.

5.2.2.2. Intensity of production. There is no record that jatropha cultivation has any impact on the biodiversity of indigenous floral species [87, citing de Padua et al. 1999]. The intensity of production is determined by the level of inputs used. The impact on biodiversity is largely unknown and not targeted in the studies assessed. Generally, the use of biofuels increases eutrophication, acidification and nitrous oxides emission compared to fossil fuels [69].

5.2.2.3. Methodological aspects. There are only three studies that have measured or observed (potential or actual) changes in biodiversity due to jatropha projects. Of these three studies, only two; Finco and Doppler [17] and Van Eijck et al. [20], made a quantitative impact assessment. In the study by Van Eijck et al., field measurements were made of an area targeted for conversion into a jatropha plantation. However, in the end this area was not actually converted. A third study, Skutsch et al. [50] made observations on (limited) deforestation in Mexico by interviewing smallholders. Interestingly, all three studies indicate possible or actual negative impacts. The other studies only describe the potential risks beforehand. Both Finco and Doppler [17] and Van Eijck et al. [20] concluded that biodiversity was negatively affected due to deforestation. However, as Ravindranath et al. [88] pointed out, policy measures may be implemented to prevent the conversion of forest and to stimulate biofuel production on marginal lands. However, it is questionable whether this would be attractive from a financial and social point of view. In Section 5.1, it was already noted that jatropha cultivation on marginal soils is financially unattractive due to very low yields. Moreover, marginal lands are commonly used by land-poor people for other purposes such as grazing and collecting forest produce (see also Section 5.6.14).

5.2.2.4. Quality judgement and knowledge gaps. Only a few reports have analysed the impact on biodiversity. Most studies that mention biodiversity have analysed the effect of previous land use but not the effect of production intensity. Typically, smallholders do not have a high intensity of production; they often do not use pesticides or herbicides. However, for plantations this is usually very different. It is only possible to determine the biodiversity impact more accurately if a baseline study has been carried out in advance. In some countries companies are obliged to carry out an Environmental Impact Assessment (EIA) if they want to receive a licence to operate. An EIA could serve as a baseline study if it is objective, reliable and of high quality.

As the impact on biodiversity is very location-specific, the results of the studies that analysed the impact on biodiversity in a specific location cannot be transferred to another area. Still, these studies may be useful in the comparison of locations and in the comparison and harmonisation of the methodologies used. Conversely, it is possible to use the results of the studies on the carbon stock of jatropha plantations for other locations. Generally, mono crop-plantations planted on newly cultivated areas decrease biodiversity. However, there are measures to overcome this, such as planting in several blocks, leaving areas of original vegetation untouched, and performing a zoning or mapping exercise on a national level to identify areas that can be converted with minimal impact. Therefore, clear guidelines are required for spatial planning that minimise negative impacts.

5.3. Social issues

Five social issues are addressed in this assessment: food security, local prosperity and well-being, labour and working conditions, land ownership and land rights, and gender issues.

5.3.1. Food security

The four dimensions of food security, as defined by FAO are: food availability, access to food, stability of supply, and utilisation of food for individuals, households, communities and larger population groupings [89,90].

In Table A-4 in Appendix A, 26 studies are summarised that included an analysis of food security impact. Of these studies, twelve mention a negative impact on food security, while no negative impact on food security was found by twelve other

studies, including the comprehensive report of the FAO. Eight studies observed a partially positive effect. The negative impact found is all due to food replacement by jatropha, either directly, by crop substitution on land, or indirectly, by a reduction in the time spent on tending food plots. Most studies focused on smallholders.

The most comprehensive study is a study by the FAO on biofuel crop production and food security in Tanzania. The research team found no significant negative impact and concluded that even a slight increase of current yields will offset any effect on food security [91]. However, two other studies in this assessment, also based on actual observations (in India and Brazil: [17,92] note that food security can be negatively affected if the cultivation of food crops is replaced by jatropha and the increased household income does not compensate this. This is highly relevant due to the low financial benefits of jatropha. Thus, food security may be affected, but there are measures to offset this effect, such as favourable working hours on plantations, sufficient wages to purchase food, and ensuring that jatropha should not replace food crops at smallholder plots, e.g. by promoting fence cultivation only. The issue of food security is also closely related to poverty reduction and rural development [20,93]. Portale [94] analysed the food security perception of jatropha contract farmers and non-jatropha farmers. The jatropha contract famers reported lower food shortages and considered their food security level higher than before cultivating jatropha, as a result of their additional income.

The issue of food security is more urgent if jatropha plantations are situated in areas with a high prevalence of food insecurity. For example, one plantation company in the South of Tanzania is situated in a region which produces just enough food for three to four months after harvest. During the remaining months people have to buy their food [95]. Specific measures may be taken to minimise impact; for example, the plantation company established a school vegetable garden in a nearby village, where local children could learn about agricultural practices which would increase food production [8]. However, among the projects visited in Mozambique by Schut et al. [85], only a few initiated food-security projects. Schut et al. [85] concluded that on the current scale this will probably not endanger food security in the short-term, but that the long-term effects are unclear. Farmers employed as labourers on plantations spent less time on their own food plots, which resulted in decreased food production [96]. Chachage and Baha [97] also observed a decline in food production because labourers lacked the time to tend their food plots. Still, measures may be taken to overcome this situation; for example, in Mozambique the workers have favourable working hours (e.g. until 4 pm) to enable them to continue working on their household farm [96]. Other measures that can be taken by plantations are the inclusion of smallholders in their business model and a plantation system that uses intercropping [98].

Mshandete [22] pointed out that even in smallholder systems the effects on food security may vary according to differences in implementation. As opposed to monocropped systems, intercropped systems provide benefits of intensification and diversification of cultivation and reduce the risks of pests and diseases. In such systems, spacing and crop choice are important [99].

5.3.1.1. Methodological aspects. Most studies base their conclusion on interviews, by asking whether people feel food insecure or asking about their diet and the number of meals they eat. The conclusion is often based on either anecdotal data and only sometimes on statistical analyses which include a control group e.g. Loos [9] and Peters [96]. One study, [94], created an index for the perception of food security, again based on the question as to whether smallholders felt that they had been running out of food in the last twelve months. Food security can be very different across local areas and even across households, and therefore the response to these questions probably provides an accurate image of specific locations. However, it is difficult to link any changes in perceived food security to biofuel projects as such changes may also be due to external reasons such as drought. Moreover, the number of respondents varies per study from 10 to more than 200. The accuracy of the analysis and conclusions of the studies may vary according to the number of sample observations in relation to the relevant population size, as well as according to the method of questioning. It is difficult to draw any meaningful conclusions about the optimal number of respondents, without an in-depth insight into the local setting.

Many studies provide more general remarks on possible effects, such as Mwamila et al. [98], who mentioned possible food crop replacement. Other studies use food production statistics from the region to give more background information and in this way enable a better interpretation of the effects of jatropha projects e.g. Habib-Mintz [100] and Finco and Doppler [17].

Some studies take a wider perspective and try to take more elements into account. For example, German et al. [101] analysed the food security situation of jatropha smallholders in Zambia by looking at the changes in land area under food crops before and after the introduction of jatropha, changes in net food production, changes in the quality of the land allocated to food crops, and the loss of revenues and/or safety nets that non-timber forest products provide in the event of deforestation. The increase in food supply that they found was possible because smallholders cultivated new areas for jatropha in which they intercropped with food crops and some food crops were planted in new areas with better soil. In places where jatropha was planted as a monoculture crop, the amount of food produced was less due to displacement.

Ewing and Msangi [93] examined various food security variables. As key indicators they used major dependence on local food and energy, agricultural land availability, and women's productive use of time. They concluded that countries with a high reliance on biomass for energy and a high incidence of hunger, such as Tanzania and Mozambique, should invest in energy technologies with positive spillovers into food production and in employment opportunities for the poor. Biofuel development may improve purchasing power and decrease the vulnerability to international price shocks. Especially outgrower schemes may induce technology spillovers into food production [93].

Although Arndt et al. [102] did not specifically look at jatropha projects, they used an interesting methodology to study food security in scenarios with jatropha production: a gendered dynamic computable general equilibrium (CGE) model based on Mozambique (see also Section 5.6.15). They concluded that the increased Gross Domestic Product (GDP) reduces poverty, but that there is a trade-off between biofuels and food availability if female labour is used intensively and as a result women are not available for food production. Modest improvements in both women's education and food crop yields can offset these impacts.

5.3.1.2. Quality judgement and knowledge gaps. To analyse the food security situation of the local population, ideally repeated measurements should be carried out that combine a sizable number of relevant factors. So far, most studies indicating whether an area is food secure or not have been unable to link this aspect to jatropha activities. If jatropha replaces food crops, the local production of food decreases; this can only be offset if the population earns enough money to purchase food, and if the market infrastructure allows such food purchases. In this assessment, several measures have been identified that can help to reduce food insecurity: favourable working hours on

plantations, provision of agricultural knowledge especially for women and avoidance of the displacement of food crops by planting jatropha in areas not used for food crops, such as hedges. However, if a project was discontinued, it remained unclear whether the local population could re-access land that was formerly used for fire wood collection and other activities, but that was subsequently appropriated by the plantation. This has happened in some cases in Africa (eg. the Bioshape plantation in Tanzania and the Sun Biofuels plantation in Mozambique), and it is potentially a serious problem. Explicitly including this aspect in the land lease contracts may avoid this problem, since often national laws are unclear about this aspect due to lack of precedence. The complex linkages between biofuel production and food security require more research, but so far results have indicated that food security does not have to be at risk if projects are carefully implemented. More comprehensive long-term studies are needed that include all major dimensions of food security. These should be based on primary data collected on site at biofuel projects. They should disseminate lessons on how to minimise any negative impact on food security. In this assessment, FAO [91] was the only study that investigated all four food security dimensions.

5.3.2. Local prosperity and well-being

Local prosperity and well-being of the local population can be achieved through increased household income and increased access to, for example, education, health facilities and energy. Furthermore, greater knowledge about e.g. cultivation techniques or technical skills by local communities through training and advice can lead to increased local prosperity.

Table A-5 in Appendix A includes an overview of the 39 studies that deal with (aspects of) local prosperity and well-being. Nearly all studies mentioned a positive impact on poverty reduction for smallholders. Only one report indicated that the poorest households may not benefit if the owners of the jatropha trees do not allow them to pick seeds; however, this study also describes positive impacts, such as increased household income [103]. There were only a few studies that mentioned a negative effect on the local economy and local employment, mainly due to the discontinuation of projects and the delayed financial gains. Five themes were frequently mentioned in the studies: impact on energy access, poverty or livelihood/local economy, employment generation, skills, and attitudes and well-being. The main findings for each theme are described below.

5.3.2.1. Energy access. Especially the use of jatropha oil by local communities has a positive effect on local prosperity and well-being because it leads to increased energy access, either through electricity generation (by using SVO or biodiesel in a generator), by using the oil in cooking stoves, or by using the by-product, seedcake, as a substitute for fuelwood or charcoal. Still, there are some socio-organisational issues that need to be taken into account. For example, Wijgerse [104] stated that increased energy access is beneficial, but that the system that was analysed in Tanzania needed improvements such as a clear ownership and maintenance structure, the installation of household electricity metres and the adoption of high efficiency lights. Broadhurst [61] compared a plantation, a smallholder (outgrower) model and a community model and concluded that all three can increase income and employment. However, if a plantation scheme is aimed at the export of the raw material, local energy security is not improved.

5.3.2.2. Poverty/local economy. The study by Peters [96] analysed the impact of a jatropha plantation in Mozambique on the households of its employees. It found that households working on the plantation had better socio-economic conditions than households in the control group [96]. In addition, the study concluded that the income and expenditures (significant for food and non-food items) increased and leisure time decreased. Microenterprise activities and the sale of cash crops increased too. In schemes in Honduras and Mali, farmers are shareholders of the biofuel company; if profits are made by the company they will be returned to the farmers [105]. In Honduras a local currency was introduced by the project, with the objective to stimulate the local economy [99,105]. This local currency was used to buy biofuel, to buy from each other, to partially pay wages or was converted back into the national currency. The study by Portale [94] revealed that the perception of economic access to credit is higher among outgrowers than non-outgrowers, probably due to the belief that a contract will create ways to access credit. The study by Arndt et al. [106] differentiated between outgrowers and plantations and concludes that the first system is “more pro-poor due to the greater use of unskilled labour and accrual of land rents to smallholders.” Mujeyi [107] indicated that wealthier households do not farm jatropha; in fact, it seems to be a crop for poor farmers. This finding is confirmed by [108]. In contrast, Bos et al. [109] observed in Mozambique that the wealthier farmers have more room to experiment and were therefore more likely to adopt jatropha. The study by Broadhurst [61] indicated that a smallholder system creates an enabling environment for local farmers and entrepreneurs. Several studies have indicated low financial benefits from jatropha [5,20]. So far, this low profitability has led to a relatively low impact on poverty levels. However, there may be other positive effects on livelihoods. Schoneveld et al. [110] mentioned that the majority of respondents (67%) who felt that their livelihood had increased due to the jatropha plantation did not consider their increased income the most important, but rather the increase in security and stability of income flows.

5.3.2.3. Employment generation. Employment levels vary according to the business model used. The efficient agricultural management systems used in plantations usually generate more employment, while smallholder models reach more people although their less efficient management leads to smaller economic benefits per person [20]. Habib-Mintz [100] observed that most jobs created on plantations were for land clearance and land preparation, which are tasks that are only required once. From an analysis of investment proposals in Mozambique, it was calculated that the jatropha companies estimate a job creation of 0.14–0.17 jobs per hectare. While the total investments for these jatropha projects equal almost 3 million $ or 1700 $/ha. One formally approved jatropha project in Mozambique provided 0.27 jobs/ha including seasonal labour [85]. The company Diligent in Tanzania had around 200 seed collectors working for them in 2009 [8].

5.3.2.4. Skills. In Mozambique it was observed that on the job training took place for skills such as pesticide spraying and tractor driving [85]. However, of the nine projects visited, not one provided formal training or education programmes. In Honduras local people were trained in the production of biodiesel, although external experts were needed for this training [105]. In addition, fifteen car mechanics received training in adapting engines. Moers [105] also observed that a degree of technical capacity is necessary in order for jatropha projects to become successful. Prakash [99] pointed out that in the six projects she evaluated, dissemination and implementation of agricultural knowledge was problematic due to extension workers without proper training and a lack of clarity among organisations about their responsibilities. Furthermore, the ratio extension workers to farmers was very low.

5.3.2.5. Attitudes and well-being. Unmet expectations and initial misinformation may lead to a decline in trust. This has been reported in 5 cases in Myanmar, Mozambique, Mexico, India and Kenya. In Myanmar people became cynical when the expected benefits did not materialise, this was probably due to a lack of proper information on agronomy and the market [111]. De Jongh and Nielsen [57] indicated a lack of trust due to the collapse of the jatropha seed price over time in Mozambique. Initially, the price of seeds was artificially high because the establishment of new plantations led to a high demand for seeds, which decreased significantly at a later stage. Also Skutsch et al. [50] indicated that too high initial expectations led to a subsequent decline in trust in Mexico. In India, 85% of farmers discontinued because jatropha had not met their expectations [49]. Moreover, misinformation, often at the start of a project, leads farmers to lose faith in the information they receive and in the organisation that supplies it; this is what happened in Kenya [5]. This misinformation at the beginning of projects was not necessarily intentional, but there is still a great lack of knowledge about agronomic practices [5,10].

Portale [94] addressed well-being by looking at life satisfaction and evaluating happiness. This revealed that jatropha outgrowers score higher on these indicators, which is probably the result of better household living conditions caused by jatropha sales. In addition, social capital (based on trust and participation in projects) was higher among outgrowers. However, in the village in which these benefits were observed, jatropha had been cultivated for a long time and relatively high prices were being paid, which may also have contributed to the positive ratings.

Many projects have had, or are expected to have, a positive influence on several aspects of local prosperity, whereas almost all negative impacts on local prosperity are due to discontinuation of the projects. This leads to the conclusion that financial feasibility of jatropha projects is essential for local prosperity.

5.3.2.6. Methodological aspects. Most studies were based on interviews and observations. For example, the study by Loos [9] investigated agricultural income, land, livestock and assets to measure welfare. However, this can only result in quantitative impact data if these data can be linked to biofuel projects, requiring at least several measurements over time. There were also studies based on potential impact rather than on actual observations. The impact on local prosperity has only recently been partially modelled or quantified for example by Van Eijck et al. [20]. They considered wages and employment in relation to unemployment rates in the region, total investment costs, local purchases, relation of local versus non-local employees and also qualitative indicators for social well-being and the risk of negative impacts in the case of project failure. Portale [94] combined several qualitative questions in her survey into an economic access index, a well-being index and social capital score, which together provide insight into the perceptions of the smallholders. Arndt et al. [106] used CGE modelling to link several aspects of poverty, which led to the conclusion that biofuel production schemes that include outgrowers generate more employment for unskilled labour. Furthermore, technology spill-overs especially can enhance economic growth and poverty reduction.

5.3.2.7. Quality judgement and knowledge gaps. The exact impact of the jatropha projects on local prosperity is difficult to gauge as this relationship is rather complex. Comprehensive methodologies are required that combine the most important variables regarding local prosperity, such as the impact on employment, income, investment in the region, labour migration, possible risks for local communities and the attitude of the local population. The methodology should also include possible employment displacement effects of plantations, and changes in income or wealth. Applying a regional input–output methodology may assist in identifying the monetary impacts of the biofuel sector on a region (e.g. [112]). However, it is necessary that regional input–output tables are available. Furthermore, the early overly optimistic yield estimates led to misinformation at the beginning of several projects. Agronomic data should be reported more accurately and completely, including soil quality, precipitation and age of the trees.

5.3.3. Labour and working conditions

Eleven studies covered aspects of labour and working conditions. They are summarised in Table A-6 in Appendix A. Five studies came to a positive conclusion, two found no effect and four found negative impacts of which some only found anecdotal evidence. Four aspects were frequently mentioned: legal issues, wages and other benefits, child labour, and health and safety. They are described in further detail below.

5.3.3.1. Legal issues. No studies observed any by-passing of the law without consequences. In Mozambique the government voided one contract when contractual obligations were not met: the business plan was not followed [21]. A weak position of smallholders is mentioned by one study [113] and there is one case in Myanmar where farmers were allegedly forced to grow jatropha; however, this claim could not be verified [114,111].

5.3.3.2. Wages and other benefits. Schut et al. [85] found that all nine companies visited in Mozambique paid at least the minimum wage. Chachage and Baha [97] observed that of 600 jobs only 90 were permanent. Since jatropha harvesting is seasonal, this is an important issue. Smallholders would like to see higher seed prices but at the same time jatropha companies that process the seeds offer additional benefits to their employees such as National Social Security Fund, medical and funeral support, credit and savings society training, courses and meals [8,115]. The study by GTZ [5] indicated that only fence cultivation is profitable for smallholders. Transport for non local workers could be improved in some cases [85]. At the plantation of Energem in Mozambique, 500 jobs were created, paying at least the minimum wage (60 $) and ending the workday early to enable workers to tend personal fields. However, although meeting the minimum wage requirement, salaries were still too low to allow workers to improve their standard of living [116]. Peters [96] identified a large difference between two plantations in the number of days absent. This might be due to the higher job opportunities in the area where the higher absenteeism occurred. Thus, wages could be insufficient to cover opportunity costs. Moreover, the ratio male/female is much higher at this plantation. The study by Ariza-Montobbio and Lele [59] observed that landless and marginal farmers in India normally migrate to nearby cities after the agricultural season. However, due to the low labour demand related to jatropha, the perennial characteristics of jatropha, and the potentially low financial benefits, these farmers now stay longer in the city to work as daily wage labourers. The company ESV in Mozambique employed 1350 workers and paid the permanent staff above minimum wage. Nevertheless, due to the financial crisis, they were not paid for nine months before the company was taken over. Two other companies in Mozambique, Mocamgalp and Sun Biofuels, employed 35 and 430 workers, respectively (in 2009), although the latter company apparently had nine-hour workdays, which is legally not allowed [116].

5.3.3.3. Child labour. In smallholder communities, it is common that children help with farm tasks; it is likely that this will include picking and dehulling jatropha seeds [103,109,115]. In the

processing companies or on plantations, no child labour has been reported. Workers have to identify themselves so that their age can be verified [21].

5.3.3.4. Health and safety. Not much has been observed about aspects of safety in the current projects. Brittaine and Lutaladio [24] (IFAD/FAO) and Proforest [87] mentioned potential poor conditions, but these were not actually observed. In addition, Chachage and Baha [97] mentioned some anecdotal stories of bad working conditions from employees of a plantation company. However, these do not seem to have been verified.[5] Safety gear is usually provided, but in one case in Mozambique a difference was observed between permanent and casual labourers, where the latter group did not receive any safety gear [8,85].

Health issues mostly relate to the toxicity of the seeds and the oil. Janssen et al. [117] found no evidence that the use of jatropha oil results in the emission of specific toxic compounds in health-affecting quantities; however, this was the only study that reported on this. Not all aspects seem to have been researched; for example, the impact on the skin has not been investigated. There are some studies on the toxicity of the seedcake. The toxic compounds (phorbol esters) of jatropha press cake degrade within 15–23 days when applied to the soil [118]. Another study by D1 Oils concluded that no toxic compounds could be traced in the chemical analysis of food crops fertilised with jatropha seedcake (Van Peer, personal communication). So far, no negative health effects have been reported other than the direct effects of seed intake, but this may be due to a lack of long-term studies.

5.3.3.5. Other issues. Differences in work ethics were observed in Mozambique between the (foreign) investor and local workers. These differences occur both on plantations and in contract-farming arrangements. Labourers did not show up for work after payday, and farmers did not honour their sales contracts because they were not used to working on a contract basis [85].

Moreover, Nielsen and De Jongh [119] observed that the peak in labour demand for jatropha coincides with the peak in demand for food crops. Still, jatropha seeds can be left on the tree for several weeks, which makes it possible to harvest jatropha after the peak labour demand for food.

5.3.3.6. Methodological aspects. The studies have a similar set-up: they are all based on interviews and observations. Therefore, the fact that some mention positive effects and others negative ones cannot be attributed to different research methodologies. However, the number of observations varies, and some reports base their conclusions on what seem to be incidents. Interviews and observations are a good way to assess labour and working condition issues because differences are local and depend on the specifics of project implementation. Some reports also provide recommendations for improvement, which could help other projects.

5.3.3.7. Quality judgement and knowledge gaps. Since working and labour conditions are project-specific, monitoring of the projects is necessary, which is what most studies do. Notwithstanding the good intentions at the beginning of a project, it is necessary to incorporate a proper exit plan in the approved business model, especially to prevent mishaps after discontinuation. So far, a proper exit plan has only rarely been drawn up. National laws mostly include aspects of working and labour conditions, so it is essential that projects ensure that they comply with national (and international) laws, and most projects seem to do so.

[5] The report mentions a case in which an employee supposedly contracted tuberculosis from the smoke in the company's cooking area. However, this disease cannot be contracted by inhaling smoke.

5.3.4. Land ownership and land rights

Land conflicts are very common in developing countries, especially in Africa. Many studies have been published on this issue, although they mostly do not focus specifically on jatropha but more generally on land deals in Africa in relation to biofuels (e.g. [120–122]). In total, 23 jatropha studies assessed or mentioned land ownership aspects; these are presented in Table A-7 in Appendix A.

Almost all studies listed in the table indicate negative or neutral impacts. Only one indicates a positive impact, namely that hedge planting can reduce boundary conflicts. There are some recurrent issues associated with obtaining administrative land rights of large plots of land. They include: unclear acquisition processes, tenure conflicts between customary and granted land rights, disputes over compensation payments (and over unclear methods), misunderstandings about exact land demarcations (in absence of adequate and coordinated land information), poor communication between the new land owner and local communities, a lack of understanding about employment opportunities, and a lack of transparency of the whole process, which creates confusion [8,51,87,91,100,122]. These issues are in part due to pre-existing issues; boundaries are often not clearly defined and land ownership is generally not documented [87,123]. Furthermore, idle or marginal common lands often provide various products and sources of income for the rural poor [51,124]. Another issue is the often very long-term lease contracts, in some cases as long as 99 years [8]. It is challenging for the local population to take in such a long period and it is also difficult to put an accurate value on land for such a long period.

Large land ownership transfers or land lease contracts are often accompanied by promises about the provision of goods and services, such as infrastructure and classrooms. However, the studies have reported several problems. Often, such promises are only made verbally by the land owners, and after a project is discontinued, no further development of the area occurs. Land access is also often unclear after project discontinuation [20,97,98,110,116]; see also Appendix B. In some countries, such as Tanzania, land rights are first transferred from the villagers to the government before the rights are transferred to the company that will plant jatropha or another crop. After discontinuation, these rights are not transferred back to the villagers, although the expected development in the area does not materialise [20,97]. Not many observations were done on resettlements, two studies in Mozambique mentioned voluntary resettlement in order to be closer to the workplace, and a study mentioned an initial displacement of 950 households which would drop to below 150 if they planned cultivation differently [85,125].

In smallholder systems with no administrative land rights exchange, land issues are much less dramatic than in plantation systems in which landownership changes. However, 93% of the jatropha growers in Tanzania responded that it is difficult to extend their land under cultivation [103]. This was also observed by Wahl et al. [126]. The studies mentioned the following reasons: customary control, a general reluctance to sell land, a shortage of suitable land and an increased population. However, in another study on Tanzania by Loos [9], of the 117 non-jatropha farmers interviewed, only 1.7% responded that a lack of land was the reason for not growing jatropha. A study in Mali concluded that land access did not change as a result of small-scale growing of jatropha [127]. A similar conclusion was drawn in Mexico [50]. Differences in land access were perceived to be related to indigenousness, gender and seniority of the villagers. Land pressure was identified as an important reason for problems with land access. Increased land pressure could lead to vulnerable groups

losing their land access or having difficulty in sustaining their land access [110,127]. Several studies indicated that planting trees is seen as claiming land ownership, which may increase conflicts [127–129]. The pastoralist Masaai tribe in Tanzania consider the large-scale growing of jatropha as upsetting their traditional lifestyle [130]. On a smaller scale, planting jatropha as a fence can also help to reduce land boundary conflicts, especially if the neighbours are involved when the lines are delineated [127]. Studies advising hedge planting include Wahl et al. [126,5].

Some studies mention alternative land ownership structures; for example, in India there are self-help groups that have exclusive harvest-rights instead of land rights [131,132]. In addition, a study by Brittaine and Lutaladio [24] mentioned an example in India where degraded community lands were rehabilitated by planting jatropha. The strategy involved the use of degraded common property resource lands held by the village council. Self-help groups of landless people and smallholders were paid per work-day as an employment creation scheme. The land and trees remained in public ownership.

5.3.4.1. Methodological aspects. Most studies were based on interviews and observations. This is understandable since there are hardly any other data available, such as court records of the number of complaints. In developing countries, bodies where communities can complain are often not well established. Some studies express a very negative sentiment, using phrases such as 'land grabbing' and 'land take-overs'. Some studies researched the amount of land available by analysing national or regional statistics [85]. However, no future projections of land pressures were included that take population growth and future food needs into account. Assessments of changes in land access (as compared to land availability) are more subjective and these changes are not well-recorded.

5.3.4.2. Quality judgement and knowledge gaps. The observations in the studies suggest that most of the problems with land acquisition and land rights are due to weak institutional frameworks and pre-existing problems with the governance of land rights and land ownership. For example, there are often no clear rules for compensation payments. A process of land acquisition is time-consuming and it takes a great deal of effort to make sure that the local population clearly understands the contractual arrangement and is sufficiently informed during the negotiations. A transparent process and optimal communication with the local population are essential. Vulnerable groups could more easily lose their land rights; therefore, these groups should be considered specifically. Studies should include various stakeholders if they want to document the process of land acquisition. More research is necessary into finding measures to mitigate reduced land access. Comprehensive analyses that take population growth into account help to assess whether and where there is sufficient land available in the future; this depends on several issues, including cultivation intensity.

5.3.5. Gender issues

So far, gender issues for jatropha have not been considered in great detail. Only four studies include a specific analysis of gender related aspects, namely Mota [19], Peters [96], ENERGIA [133] and Arndt et al. [102], although the ENERGIA study does not exclusively consider jatropha. Other studies have observed gender differences but have done so as part of a broader analysis framework comprising multiple aspects. A total of 11 studies have covered gender-related aspects; they are presented in Table A-8 in Appendix A.

Most studies conclude that the production of jatropha has no effect on gender equity (so far), only two found a negative impact and two found positive impacts. Negative impacts (mentioned in the two studies) are due to pre-existing gender differences, namely the fact that it is women who cultivate food plots and have domestic tasks. Working as an employee on a plantation reduces the time available for these tasks, which still need to be fulfilled [19,96]. Although in Mozambique, it was observed that favourable working hours at the plantation enabled women to keep tending their household food plots [96]. A calculation by [102], shows that also yield improvements can offset the effect of reduced food production by women. Positive effects are related to increased energy access, which reduces women's tasks, such as collecting firewood and milling maize.

It remains unclear whether increased energy access leads to increased gender equality. A study by Verhoog [134], which did not specifically focus on jatropha, suggested that women's empowerment is not automatically improved if access to energy is increased. This is only the case if the project specifically focuses on the empowerment of women. This last point is confirmed by Clancy et al. [135]. Nevertheless, the study by ENERGIA found that projects that increased energy access automatically improved the lives of women. One case study in that publication mentioned that women could charge their batteries in the village. In the past, batteries could only be charged with the help of a male relative since the charging point was 20 km away and women do not own bicycles or motorcycles in rural Cambodia [133].

De Jongh and Nielsen [57] did not specifically analyse gender aspects but they do mention two studies that found no gender bias in the adoption of jatropha. However, they also state that these studies were based on only a few interviews and that more comprehensive studies are required.

Possible gender problems that can be associated with the production of liquid biofuels in general were described in a study by the FAO [136]. From other sectors, they found documentary evidence that gender gaps occur, for example due to the lack of access to resources for women. Land ownership is often more difficult for women, and related to this, access to credit, because women do not have land that they can offer as collateral. Furthermore, if energy crops are planted on marginal land, this has a greater risk of pushing out women, since they are mostly the ones who collect commodities such as firewood from these grounds. Although the interviews conducted by Salfrais [127] revealed no worsening in the situation of women's land access after jatropha cultivation started in Mali, she stated that this may change in the future. Increasing land pressure increases the risk that women as well as other vulnerable groups (non-founding families and younger members of the community) lose their land access rights. In one case, a men's association pressed the women's association to discontinue cultivating one hectare of jatropha, which shows that men have control over land access [127]. In some countries jatropha cultivation is carried out by men, in others by women or by both. It is also very common that older children help with farm tasks. In Mali, women traditionally extract oil from jatropha for medicinal purposes [24]. In Mexico, jatropha cultivation and seed selling are considered a man's business, whereas dehulling, which is quite an arduous task, is performed by women [50].

Women (and children) often pick seeds. In Zimbabwe, women are also involved in soap and candle making, which to some extent has led to empowerment because it generates extra household income [137]. Henning indicated that in Mali, men initially allowed women to harvest seeds for soap making, but when the women turned this into a cash-generating activity, the men wanted a share of the profits. This led to some loss of interest in the project since the project goal was to promote women's participation (Henning 2004 cited in [24]. This mechanism of appropriation by men is also described by [138]). If plantation owners pay on a piece-rate basis, this can discriminate against women if the job requires physical strength. Plantation

owners sometimes tend to prefer women workers because they feel they can pay them less [136]. The study by Arndt et al. [102] showed that skills-shortage among female workers limits poverty reduction, and policy should therefore be addressed to increasing women's education. A study by Portale [94] concluded that women decide which crops to grow in only 25% of the households.

5.3.5.1. Methodological aspects. Almost all studies were based on interviews and observations, and only one was based on a model that includes several aspects. This study, by Arndt et al. [102], looked at gender implications for (jatropha) biofuel production with the help of a gendered CGE model. Portale [94] constructed a gender index by asking the respondents (201) who was responsible for the household crop decisions. Both men and women had to answer, and this revealed no difference, which led to the conclusion that the rate was similar to the national average.

The main gender differences observed in the studies seem to be derived from pre-existing gender differences. There are some similarities but also differences among the countries under study. For example, farming activities are a task for women in Mozambique [19]. This then translates into jatropha cultivation also being performed by women as observed in the same study; only women labour was used for farming jatropha in 62 out of 70 households. In contrast, Tanzania farm labour and jatropha cultivation are performed by both men and women [139].

5.3.5.2. Quality judgement and knowledge gaps. So far, gender aspects have not been well analysed for jatropha projects. There is a lack of long-term studies that systematically collect gender-disaggregated data. Moreover, evaluations of energy projects very rarely use gender analysis, something which had already been noticed by Clancy et al. [135]. Nevertheless, there are more general gender studies that include analyses of the effects of biofuel production.

6. Discussion and knowledge gaps

Table 4 summarises the economic, environmental and social aspects that have been covered well by current literature, as well as those that have not yet been covered well. The methodologies applied by the studies are also indicated in the table, and remarks are made on any shortcomings.

6.1. Economic aspects: assessment

There are still many gaps in the information about economic issues. CBAs have been undertaken for smallholders (1 ha plantations, and some intercropping set-ups and hedge plantings), and a few from a national (macro) perspective, without making any specific reference to business organisation and production sizes. For large-scale plantations, CBAs are much less available (e.g. in [20,16]). Private companies have also undertaken CBAs, but these are not publicly available. The majority of CBAs rely on unreliable and often unrealistic yield data that do not match the findings about observed yields (1000–2000 kg dry seed ha/yr for mature plantings). CBAs often take a time horizon that is too short (10 years or less) to be able to reliably assess the long-term average jatropha viability. There is a general lack of information outside the Eastern/Southern African and Indian context, although in part this is due to the lack of studies in Spanish and other languages besides English that have been taken into account in this assessment. Data on the financial viability of plantations are almost completely missing and not many plantations are in full operation, although there are some data about their establishment costs and running costs. There are also hardly any studies that systematically compare the financial feasibility of outgrower schemes and centralised plantations of similar production volume or land area (only [20,61] to some extent). Data about the cost of SVO and biodiesel production in facilities of different scales are scarce, especially in Africa where commercial oil production is only just beginning.

6.2. Environmental aspects: assessment

Additional research is required to fill in the knowledge gaps on environmental aspects by studying land use change, including the effects from above ground, below ground biomass and soil-bound carbon and nitrogen on initial carbon debt. Lal [140] claims that terrestrial pools of carbon can act as a sink for atmospheric CO_2. Optimally managing the soil carbon pool must be the basis of any strategy to improve and sustain agronomic production, especially in developing countries. George and Cowie [141] point out that soil organic matter (SOM) strongly influences many soil properties and as such is a primary indicator of soil health. The amount of SOM in soil is a function of climate, topography, parent material, biology and time (Rice, 2005, in [141]). Loss in soil carbon in the establishment of energy crops, or as a result of residue removal, could negate the climate change benefits of using bioenergy to displace fossil energy sources [141].

Moreover, more reliable data is needed to gain better insight into trade-offs and related impacts, for example using marginal land with increased fertiliser versus using more fertile land, adopting large-scale centralised processing with long feedstock transport distances versus centralised small-scale production and local use, and using seedcake for fertilisation versus using seedcake for energy use. Not many studies have analysed the impacts on biodiversity and baseline studies are lacking as well as long-term impact studies. So far, no quantitative research about the soil erosion prevention capacity of jatropha has taken place [81].

6.3. Social aspects: assessment

The knowledge gaps on social aspects are on food security. Comprehensive studies on food security that include all four aspects defined by the FAO are not well covered (food availability, access, stability of supply and utilisation of food). Studies that examine the relationships between these different aspects are especially lacking. Regarding local prosperity, hardly any information has been found on local employment for smallholders or impacts on the local economy. Labour and working conditions on plantations have been documented quite well by company documents and studies that include field observations, although it is still unclear as to what extent plantation workers actually develop skills. National and international laws seem to prevent most negative impacts (e.g. on health), although monitoring remains necessary. Land rights issues mostly emerge due to pre-existing problems; the acquisition of large amounts of land for biofuels can bring these latent issues to the surface. More studies are required that include measures to mitigate reduced land access by communities. Moreover, studies that include projections on population growth can assist governments or communities to make sure they maintain enough land for future food production. To properly assess gender issues, gender-disaggregated data is required on e.g. employment, energy access and so on.

In this analysis, country-specific issues are not covered; these include political and institutional issues, land availability, culture and climate. Some other issues only came up in individual countries, for example in Mozambique. In this country, Schut et al. [21] observed that most biofuel companies aimed at being located in places with a good infrastructure, high population density and good agricultural conditions. This means the rural

Table 4
Literature coverage and knowledge gaps on socio-economic and environmental issues, and an overview of applied methodologies.

Aspects	Methodologies applied	Data availability	Remarks
Economic aspects			
Cost benefit analysis	cashflow accounting methodologies (IRR, NPV, pay back indicators)	Mainly estimates or extrapolations	More analyses based on real data are starting to be published. Still, the assumptions have a high degree of uncertainty.
Set-up, running and processing costs (SVO, biodiesel, briquettes)	Analysis with business proposals	Very difficult to acquire	Not publicly available, companies do not share data, and no large amounts are currently processed.
Yield/seed sales revenue	Literature and observations (not long term)	Extrapolation of data based on short term and specific locations	Very anecdotal information, long term studies on agronomic practises ongoing
Value of by-products	Estimated or observed (few cases)	Hardly available	Market still not developed, necessary to find higher value by-products
Environmental aspects			
Climate change (GHG balance)	LCA methodology (different tools available)	Data on processing is available, carbon stock data as well but LUC location specific data often lacking	Still based on many assumptions. Data is especially lacking on acidification, eutrophication and nitrous oxide emissions and how to minimise these. Findings from studies are hard to compare, mainly owing to differences in boundary and fossil base-line assumptions and differences in treatment of Jatropha by-products. Also depending on the specific LCA tool that is used. Treatment of land use change (LUC) impact on GHG either missing or taken into account by using a lower and upper boundary.
Nitrogen contributions to GHG	Calculations based on estimates	Hardly available	Are only partly included
Biodiversity	Observations, estimates, field measurements (including satellite measurement)	Only very site specific, more data required	Impact of jatropha is unknown, relation between intensity of production versus biodiversity is unknown. Land use change important, so far inadequately taken into account.
Social aspects			
Food security	Interviews, observations, analyses of background information (statistics) and CGE modelling.	Anecdotal information and back ground data is available	Studies are required that link availability, access, stability and utilisation and quantify and predict these impacts.
Local prosperity	Interviews, observations, analyses of background information (statistics), CGE modelling and design of (wellbeing) index based on primary survey data.	Anecdotal data available	Impact on different aspect signalled: local use, employment, impact on local economy, skills, attitudes. Studies that quantify the impact on local economy are hardly available.
Labour working conditions	Interviews and observations (nr of observations vary).	A reasonable amount of data available, project specific	Aspects of child labour, discrimination, safety, freedom of trade union, education and training. Well documented, by means of company documents and national laws. Monitoring necessary by objective body.
Land rights (land availability and access)	Interviews, observations, analyses of regional statistics.	Large amount of literature available on the context	– Studies that include future projections on land availability are required. – Studies that look at measures to mitigate reduced land access are required.
Gender	Interviews, observations, gendered CGE model, design of (gender) index based on primary survey data.	Almost no gender disaggregated data available	Gender analysis in the evaluation of energy projects are lacking.

population may not be targeted. Because so many different projects and countries are analysed in this study, most project set ups have been covered. So, although e.g. the number of studies that covered Latin-America was limited (due to a lack of published studies in English and the limited amount of ha planted), the project set up is not very much different from the set up in the other continents and therefore the lessons and recommendations in this assessment can be applied across multiple countries. Whether or not biofuels are stimulated and facilitated by the government makes a large difference in the potential success of biofuel projects [8,64,114,132,142,143]. These studies conclude that there is a need for biofuels to be integrated within a broader framework of investment in rural infrastructure and human capital.

In this assessment two business models were identified and analysed separately when possible. However, there are more models that may be used in bioenergy projects. A distinction can be made between models that describe production systems, such as hedge cultivation, plantation or a mixture, and those that describe the organisation, for example government, farmer or corporate centred or multipartite (joint venture between state, private company or NGO and farmers), there are also combinations (e.g. nucleus estates) and informal models [51,144,145]. Studies including Bijman et al. [144], Van Baren [145] and Vermeulen and Cotula [146] describe possible models for smallholders and the problems that could be encountered, namely high costs and risks, and market uncertainty. Furthermore, in India there are self-help groups, described by Wani et al. [131], and in Honduras a model is used in which farmers own a share in the processing company, described in [105,147]. As yet it is unclear what the performance is of these and possibly other business models that have already been or could still be developed. More research is required on the various types of business models and their impact.

7. Conclusions

Despite various methodological drawbacks in the studies covered in this review, it can be concluded from this assessment that current-generation jatropha projects are barely financially viable and some may even operate at a loss. This is especially true for plantation settings and is mainly due to the higher input intensity of plantations combined with still limited yield levels and limited valorisation of by-products. It has also become clear from this review that financial viability for smallholders can only be achieved if limited inputs are used and if opportunity costs for labour and land are low. In the longer term, yield increase to above 2–2.5 t/ha/yr (the reported technical maximum is 7.8 t/ha/yr) is necessary as well as improved value addition of by-products such as seedcake and glycerine, which may be used in the production of energy, fertiliser, soap, bio-pesticide, and other products. The methodological drawbacks that have been found in the studies, such as no full CBA analysis, lead to large differences among the studies. The largest profitability differences found among the studies are due to variations in seed yield (3000–7000 kg/ha/yr), discount factors and time frames that were chosen, and whether land and labour costs were fully included in the cultivation cost calculations.

Environmental impacts have been found to vary greatly per location, but in general plantation schemes have a higher risk of pervasive impacts than smallholder projects. Most studies (26 of 38) indicate a significant GHG benefit over fossil fuels. An additional 11 of these 38 studies concur, provided limited inputs are used and there is no loss of high carbon stock, which is possible if jatropha does not replace forest land or biodiversity hotspots. However, it should be noted that most studies in the environmental category focused one-sidedly on energy and GHG balances and often did not incorporate complex aspects such as land use change effects. So far, more indirect effects of jatropha seed cultivation, for example the disruption of nutrient cycles, have not received any attention either. Three studies reported a loss of biodiversity (in Brazil, Mexico and Tanzania); this was found to be caused by deforestation. Conversely, planting jatropha as an addition to current land cover can also help regenerate soil conditions and may increase biodiversity.

The analyses of social aspects have revealed minimal negative impacts from ongoing projects so far, but discontinuation of projects clearly affects the local communities, not only through loss of income and uncertainty of land re-access, but also through a more negative attitude towards new projects. However, non-financial benefits, such as employment security, training possibilities (both for skilled labour and for smallholders), an increased sense of connection to ‘foreign’ projects, fostering openness to change, and a possible increase of energy security, are considered important by many local parties. Therefore, if financial feasibility can be increased, jatropha cultivation can be regarded as an opportunity to realise social development goals for workers and smallholders. Communities in regions suitable for jatropha are often vulnerable; for example, food security is often already problematic, leaving little room for failure. Therefore, projects are needed that reduce the risks for these smallholders, for example by offering an additional cash crop (e.g. from hedges or from hitherto unproductive land) or improved energy access.

For jatropha to become a viable biofuel in those markets, its whole value chain needs to become more profitable. It has already been emphasised that there is a need to find higher-value uses for by-products (especially seedcake). Other important ways forward include achieving greater oil-processing efficiency, developing seed varieties with higher and more reliable seed yields under semi-arid conditions, and optimising cultivation practices. These challenges require sustained effort over longer periods of time.

This assessment found that there are still many gaps in information and knowledge, and also a lack of consistency in data collection. Most data found in the studies was hard to compare because it was based on different methodologies (energy balance versus GHG reduction) or used different assumptions (for example regarding discount rates, yields and planting distance), and gave values in different (functional) units (for example electricity production in the Netherlands versus 1 t biodiesel produced). The studies should provide more extensive information about which methodology was used, be more explicit about their choices and assumptions, and indicate the sources or information that their conclusions are based on. Moreover, the lessons learned from the projects are fragmented and there does not seem to be a great deal of exchange between projects. In addition, authors do not frequently compare their results with those of other authors. Information sharing and benchmarking practices could assist the entire jatropha community to better understand the underlying causes of the large variations and at times contradictions in the findings.

Methodologies to analyse economic aspects are available, for example cashflow accounting using NPV, IRR and Cost Benefit Ratio indicators. However, the data necessary to perform these calculations is often missing. There are also various methodologies for assessing environmental impacts; LCA methods including or excluding land use change have been developed, and these are now available specifically for the assessment of jatropha biofuels. However, again, the field data required for accurate calculations (of for example a GHG balance) is difficult to obtain since this data varies by location. For social issues, most methodologies have been based on qualitative data such as (sometimes limited) observations and interviews. This could be sufficient to determine for example working and labour conditions or the status of land ownership and land rights. Still, for the assessment of food security and local prosperity, it would be preferable to have comprehensive frameworks that can quantify impacts (e.g. through simulation modelling). However, so far methodologies to quantify the impact of these factors have hardly been developed.

8. Recommendations

Our recommendations have been grouped by addressing three groups of stakeholders: researchers, project practitioners and government bodies.

8.1. Researchers

- More data should be collected about the expected profitability, and more reliable, observed yield figures should be used to conduct CBA assessments.
- Research should focus on improving profitability by finding higher-value uses for by-products, achieving greater oil-processing efficiency, developing seed varieties with higher and more reliable seed yields under semi-arid conditions, and optimising cultivation practices.
- More research is required to gain better insight into trade-offs and related environmental impacts, for instance using marginal land with increased fertiliser use instead of more fertile land.
- Accurate and complete reporting on scientific measurements can assist in creating realistic expectations.
- All linkages and aspects related to food security should be analysed to arrive at a greater understanding of the food security impacts caused by plantations.
- The impact on labour conditions should be monitored as employment is being scaled up.
- Quantitative analyses are required to gain better insight into the impact on local prosperity.

8.2. Project practitioners

- An independent mediator should be involved in land acquisition processes.
- Land pressure should be taken into consideration before activities in a certain region start.
- It is necessary to experiment with alternative business models, in which the community is a business partner.
- Suitable working hours should be provided so that (female) workers can tend their household food plots.
- Attention should be paid to fair pay, the inclusion of gender in project design, women's training and education and early involvement of women in projects.
- Realistic expectations for example on yields should be disseminated.
- Jatropha should not be planted on grounds where it replaces common property areas on which the local population collects fuel wood and fodder, or projects should include viable alternatives for the loss of these resources, for example wage income and biogas.
- Local purchases (of for example food, drinks and construction materials) should be encouraged in order to ensure that a large share of companies' investments stays within the region or country.
- Deliberate attempts have to be made to ensure that plantations create technology spill-overs, through training and education.
- Local populations need to be provided for in case companies stop their activities, for example by ensuring that local food plots are not neglected and that land access should not be decreased without compensation after discontinuation.
- Investors themselves should consider a gradual upscaling strategy, to enable gradual learning-by-doing without overstretching their finances and organisational capacity.

8.3. Government bodies

- Economic sustainability (financial viability) should be included in biofuel sustainability certification schemes, which is currently not the case.
- An exchange between the projects of any lessons learned should be promoted to prevent similar pitfalls.
- Zoning regulations for large land-based investments may need to be introduced and observed. Incentives should be provided to promote investments in remote poor rural areas.

Acknowledgements

This study was partly funded by NL Agency (current name Netherlands Enterprise Agency, RVO.nl) in the framework of the Global Sustainable Biomass Programme and by the Responsible Innovation research programme of the Netherlands Science Organisation (NWO). The authors would like to thank Kees Kwant, Carmen Heinze and Sietske Boschma for their support. Furthermore, we would like to thank Edward Smeets and Raymond Jongschaap, who worked with us on earlier versions of the study.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2014.01.028.

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